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FRACTURE MODES IN NOTCHED ANGLEPLIED COMPOSITE LAMINATES

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ABSTRACT

A unique Lewis Research Center analytical capability, the Composite Durability Structural Analysis (CODSTRAN) computer code is used to determine composite fracture. Fracture modes in solid and notched, unidirectional and angleplied graphite/epoxy composites were determined by using CODSTRAN. Experimental verification included both nondestructive (ultrasonic C-Scanning) and destructive (scanning electron microscopy) techniques. The fracture modes were found to be a function of ply orientations and whether the composite is notched or unnotched. Delaminations caused by stress concentrations around notch tips were also determined. Results indicate that the composite mechanics, structural analysis, laminate analysis, and fracture criteria modules embedded in CODSTRAN are valid for determining composite fracture modes.

Key Words: Composites; Graphite/epoxy; Fracture; Fracture modes; Stress concentrations; Finite element analysis; Fractography

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1.0 Introduction

The ability to assess composite durability and structural integrity is dependent in part upon correct identification and quantification of damage mechanisms. The purpose of this research activity is to develop capabilities for defining fracture modes in notched angleplied laminates. After defining the damage mechanisms, progressive fracture in a laminate can be predicted. A unique Lewis Research Center analytical capability, the Composite Durability Structural Analysis (CODSTRAN) computer code is used. Scanning electron microscopy (SEM) is used to verify that the fracture modes predicted by the code are correct.

CODSTRAN embodies an upward integrated mechanistic approach whereby composite micromechanics theory is used to generate ply properties from constituent (fiber and matrix) properties. Structural analysis, using the generated ply material properties is performed given known forces and/or displacements by the finite element method. Ply combined stresses are recovered from the predicted element stresses using laminate theory. Local combined stress fracture criteria are applied to determine whether any ply damage has occurred. When there is damage in a ply, the material properties of the corresponding element are modified accordingly. When all plies comprising an element have been damaged to the extent that they can no longer sustain loads in the longitudinal, transverse, and shear directions, the element is assumed destroyed and progressive or brittle fracture is defined. A step-load iteration scheme is followed until complete specimen fracture in the model occurs.

Experimentally, graphite/epoxy unidirectional and angleplied laminates were loaded in uniaxial tension to fracture using the Real-time Ultrasonic C-Scan (RUSCAN) testing apparatus. By using the RUSCAN facility, defect growth as it progressed in the laminate during loading was monitored. The fracture

surfaces were then cut from the fractured specimens and prepared for the scanning electron microscope. The surfaces were observed and the fracture modes of the angleplied laminates identified. Photomicrographs were taken to preserve the image identifying the observed mode.

The laminates tested and analyzed were 2 in. wide specimens or models. Three types were studied: solid coupon-type specimens, specimens notched with centered through-slits, and specimens notched with centered through-holes. The material properties and ply orientations of the graphite/epoxy laminates used for testing were input data for the CODSTRAN analysis. Comparisons between analytically predicted fracture modes and observed phenomena, either by ultrasonic C-Scanning or scanning electron microscopy, were made.

This report describes the analytical methods embodied in the CODSTRAN computer code, and the nondestructive (ultrasonic C-Scan) and post-mortem (SEM) experimental procedures used to verify CODSTRAN predicted results. The predicted and observed fracture modes are compared and the combined stress states responsible for causing fracture are discussed in detail.

2.0 Analytical Methods for Predicting Fracture Modes

Fracture modes in fiber composites are analytically determined by using an "upward-integrated top-down-structured" approach as incorporated in the Composite Durability Structural Analysis (CODSTRAN) computer code (Refs. 1 and 2). The primary purpose of CODSTRAN is the prediction of composite structural durability. To accomplish this, an iterative procedure whereby composite mechanics, structural analysis, laminate analysis, and combined stress failure criteria are coupled to determine damage to the composite structure due to hygrothermomechanical loads. By doing a stress analysis and subsequent failure

criteria application at each iteration, progressive fracture can be defined and the corresponding fracture mode predicted.

The analysis of fiber composites starts with either the constituent (fiber and matrix) mechanical, thermal, and hygral properties or corresponding ply properties. If the constituent properties are given, the ply properties are generated using simplified composite micromechanics equations (Ref. 3). Using the known ply orientations, the membrane stiffness coefficients are calculated for the laminate. Finite element material property cards are generated from these coefficients for the stress analysis. The NASTRAN finite element code (Ref. 4) is called to perform the stress analysis. Modeling the specimen with finite elements enables the investigator to obtain laminate level strains and stresses at the discrete points corresponding to the stress points of the elements. Ply level strains and stresses are then recovered from the laminate stresses using laminate theory and the structural to material coordinate system transformation.

Using one of two available combined stress failure criteria, damage is determined on a ply by ply level at each finite element. Interply delaminations are defined by limiting the adjacent ply relative rotations to an upper value (Ref. 5). If intraply damage has occurred in any of the plies, the stiffness coefficient of the corresponding element is reduced in the direction of the damage. In addition to determining that damage has occurred, the fracture mode is also predicted. If all plies comprising an element cannot sustain load in any direction, longitudinal, transverse, and shear, that element is considered destroyed and it is purged from the finite element mesh. In the case of element damage and/or destruction, the succeeding iteration is run using the same load (nodal point forces). This scheme is followed until progressive fracture causes laminate fracture or until stress equilibrium is

achieved. If an iteration is run where no element damage or destruction occurs (stress equilibrium), the succeeding iteration is run with an updated (increased by a predetermined amount) load.

Three different finite element meshes were used for the analysis of the solid, notched with a slit, and notched with a hole models. Homogeneous membrane and bending elements are used to run a plane stress case with material anisotropy. In all cases uniaxial tension was applied as nodal point forces at one end while the other end of the specimen was fixed. The number of elements, nodes, and degrees of freedom varied for the different models.

3.0 Procedures for Experimental Verification

All phases of the experimental program used to detect fracture modes are described in this section. The experimental test and results are used in this study to verify the validity of the analytical procedures described in section 2.0. The predicted and observed fracture modes are compared to indicate whether the failure criteria being used in CODSTRAN is accurate for predicting initial failure given combined stress magnitudes. The algorithm used to determine the actual fracture mode is then verified.

Graphite/epoxy composite made from Fiberite 1034E prepreg (934 resin matrix and Thornel 300 graphite fibers) was the material system used in this study. Twelve inch by 18 in. 4 ply panels with orientations $[\pm\theta]_s$, where θ = 0°, 3°, 5°, 10°, 15°, 30°, 45°, 60°, 75°, and 90° were fabricated using a pressing procedure. Individual plies (prepreg) were placed in the desired orientations in a 12 by 18 in. mold. The mold was placed in a press with temperature and pressure controls. The following procedure, specified by the manufacturer, was used to laminate the plies: (a) apply contact pressure to the mold and raise the temperature to 240° F, (b) apply 100 psi pressure and

set the cure temperature at 350° F, hold for 2 hours, (c) cool the press to 150° F after lowering the pressure to contact pressure only, and (d) remove panel from mold.

From each panel, 2 in. wide by 18 in. long specimens were cut using a diamond tipped cutting wheel. Two types of full penetration notches, slits and holes, were machined into the specimens. Slits, centered accurately across the width (tolerance: ±0.002 in. from the specimen center line) and roughly along the length were made with an ultrasonic milling machine using abrasive slurry. Slit dimensions were 0.25 by 0.05 in. Centered 0.25 in. diameter holes were machined using a mandrel (core drill), plated with diamond abrasive. Each specimen was tabbed with 2 in. wide beveled aluminum tabs. The tabs were bonded to the specimens using 3M's AF 163 adhesive film.

All specimens, notched and unnotched, were loaded in uniaxial tension until fracture occurred. Step-wise load increments were used to allow for ultrasonic C-Scanning of the stressed specimens. Ultrasonic C-Scanning was done on the Lewis Research Center's unique Real-Time Ultrasonic C-Scan (RUSCAN) experimental facility. Briefly, RUSCAN is used to image defects and defect growth in composites based upon the attenuation of an ultrasonic signal passed through the specimen (Ref. 6).

By utilizing ultrasonic C-Scanning the location and extent of the damage in a stressed composite specimen can be monitored. The experimental results are then used in several ways. The first is to verify that the damage progression pattern predicted by the CODSTRAN computer code is correct. Secondly, the C-Scan results reveal the area of fracture initiation that should be studied in detail when assessing the fracture mode by scanning electron microscopy.

The fracture mode(s) in each specimen were observed and recorded with an AMRAY 1200 scanning electron microscope (SEM). To observe the fracture modes a

segment or piece of the fractured surface located near the original notch tip or from an area of interest determined by the C-Scan is cut off. The segment is mounted on an aluminum seat and coated with a 200 Å thick gold film. The gold film increases the electrical conductivity of the specimen which in turn improves transmission by the SEM. Photomicrographs revealing the fracture mode(s) can then be obtained.

4.0 Results: Fracture Modes and Surfaces

The laminates being analyzed to determine fracture modes in fiber composites are the notched tensile specimens described in section 3.0. Analytically, the CODSTRAN computer code and its attendant methodologies are used to determine fracture patterns and modes. Experimentally, specimens are loaded in uniaxial tension and ultrasonically C-Scanned at predetermined load increments to scan for damage while the composite is stressed. Scanning electron microscopy is used to study the fracture surfaces of the fractured specimens to determine the fracture mode(s) thus verifying the CODSTRAN predicted results.

Figures 1, 2, and 3 show typical CODSTRAN generated results from finite element models of the solid, notched with a slit, and notched with a hole specimens, respectively. The results shown are from the analysis of a 2 in. wide, $[\pm 15]_s$ specimen. For all three cases the figures show damage and fracture load and fracture progression. As evident from the fracture loads, the specimens fractured into two distinct pieces at the same load where damage first occurred. This is the brittle fracture phenomena characteristic of graphite/epoxy angleplied laminates where primarily the linear behavior of the fibers are responsible for the composite strength.

Typical fracture modes as observed by scanning electron microscopy are shown in Fig. 4. The photomicrographs shown are representative of the primary

modes of fracture in the angleplied graphite/epoxy composites being studied. In Fig. 4(a), a tiered surface caused by fiber fracture indicates a longitudinal tensile fracture mode. Figure 4(b) shows an irregular fracture surface covered extensively by matrix hackles indicating an intralaminar shear fracture mode. The smooth surface in Fig. 4(c) shows clean fiber surfaces along the fiber length with limited matrix cleavage revealing a transverse tensile mode of fracture.

The fracture modes for all laminates, solid and notched, as predicted by CODSTRAN and observed by SEM are summarized in Tables I and II, respectively. A complete description of fracture modes in fiber composite unidirectional and angleplied laminates as determined by scanning electron microscopy is found in Ref. 7. Predicted and observed predominant fracture surface characteristics and interpretation of the stress concentrations and composite damage that cause laminate fracture are discussed below. In addition to determining mode(s) of fracture, the laminate fracture loads were recorded experimentally, using the RUSCAN facility, and predicted analytically using CODSTRAN. These results are summarized in Table III. Also found in this table are the percents of the fracture loads where composite damage first occurred.

As noted in Table I, the unidirectional composite is predicted to fracture due to longitudinal tension with intraply shearing occurring at the notch tip in notched specimens. SEM results show a tiered fracture surface caused by fiber fracture (Fig. 5). The matrix hackles seen on the photomicrographs are evidence of intraply shear occurring on shear slip planes in the notch tip zone. Shear stress magnitudes that cause shear fracture around a notch tip are shown in Fig. 6. As seen the actual concentration is about 10 percent of the applied stress at the notch tip. This magnitude is sufficiently large to induce intralaminar shear fracture when the applied axial stress exceeds about

100 000 psi based on a typical intralaminar fracture stress of about 10 000 psi. Therefore, as applied stresses increase, the shear stress exceeds the shear strength of the composite causing the notch tip zone to be susceptible to shear fracture.

Another phenomena associated with unidirectional graphite/epoxy composites is the occurrence of progressive fracture (Ref. 2). Progressive fracture results when a laminate is able to sustain increased loading even after composite damage has occurred. Figure 7 illustrates the principle of progressive fracture, showing the composite damage pattern as it propagates due to increasing loads applied to the unidirectional composite. Note from the figure the shifting stress concentration as the damage extent increases. The stress concentration zone moves with the advancing damaged region and as pictured is not so severe, in terms of rapid drop-off, after damage occurs. Hence, the explanation for progressive fracture as observed in laminates where stress concentrations of sharply increasing contours are responsible for initiating fracture.

Angleplied laminates of orientations $[\pm3]_s$, $[\pm5]_s$, and $[\pm10]_s$ all exhibit progressive fracture and experience fracture modes similar to the unidirectional composite (see Table I). The fracture strengths of these laminates is a fiber dominated property except where shear stress concentrations around defects cause shear fracture. In the case of notched specimens, the flaw or defect affects the combined stress state, tripping an otherwise nonpresent fracture mode typically found in solid laminates of the same ply orientation. Typical C-Scan results for this angleply range are found in Fig. 8. Here damage in the $[\pm10]_s$ laminate, notched with a through-hole, has arisen in the notch tip zone as well as at the specimen free edge where delaminations are found.

In angleplied laminates of orientations $[\pm15]_s$, $[\pm30]_s$, and $[\pm45]_s$ CODSTRAN predicts an intraply shear mode of fracture in notched and unnotched specimens (Table I). SEM photomicrographs of the fracture surfaces from the $[\pm15]_s$ notched laminates reveal evidence of intraply shear brittle fracture. Figures 9(a) and (b) show fracture surfaces from the specimen with through-slit and specimen with through-hole, respectively, covered extensively with matrix hackles. A similar surface morphology, taken from the notched $[\pm45]_s$ laminates is seen in Figs. 10(a) and (b). Here, as in the $[\pm15]_s$ angleplied layup, the presence of matrix hackles provides clear evidence of intraply shearing. For this range of angleply where fracture is primarily due to intraply shear, the CODSTRAN predicted results compared favorably with SEM evaluations.

The angleplied laminates with ply orientations between ±15° and ±45°, inclusive, tend towards brittle fracture. Note from cross referencing Table I with CODSTRAN results in Table III, that with exception of the cases where delaminations occurred at loads lower than the fracture loads, results indicate fracture was catastrophic. This means that no intraply damage occurs at loads prior to the fracture load being attained.

As predicted by CODSTRAN interply delaminations were to be sustained in the notch tip zone in laminates with ply orientations of $[\pm30]_s$, $[\pm45]_s$, and also $[\pm60]_s$. These predictions were verified by RUSCAN as seen in Fig. 11 where delaminations around the notch tip in the $[\pm45]_s$ laminate with a through-slit are noted.

Since the combined stress failure criteria used in CODSTRAN to predict intraply damage is applied at the ply level, the ply stress magnitudes should be considered in terms of how they affect composite fracture. For the unidirectional composite it is obvious that the laminate stresses corresponded to the ply stresses. For angleplied laminates however, the differences can be

significant. Consider Figs. 12 and 13 where shear stress concentrations found at the slit tip in the negative plies of the $[\pm 15]_s$ and $[\pm 45]_s$ laminates have been proven to be of sufficient magnitude to cause intraply shear fracture. The laminate level shear stress along this same line however, is zero because of laminate and geometrical symmetry. Note that despite the large stress in the fiber direction, the fiber strength being much greater, relative to the ply shear strength, precludes that the shear damage will occur in the slit tip zone as well as throughout the entire specimen. This damage then is ultimately responsible for the intraply shear fracture mode in this range of angleply.

In angleplied laminates of orientations greater than $[\pm 45]_s$, the mechanical properties are matrix dominated as evidenced by the SEM photomicrographs shown in Fig. 14. Here clean fiber surfaces with some obvious matrix hackles in the $[\pm 60]_s$ laminate (Fig. 14(a)) and clean fiber surfaces with small amounts of matrix cleavage in the $[\pm 75]_s$ laminate (Fig. 14(b)) are evidence of a predominantly transverse tensile fracture mode. Reviewing Tables I and II for analytical and experimental results shows transverse tension to be the cause of fracture in this range. Some intraply shear fracture does occur in the $[\pm 60]_s$ laminate in planes of shear around notch tips as the plies fracture and intraply slippage occurs. As seen this is verified in Fig. 14(a) by SEM. Transverse tensile fracture is a brittle fracture mode, being a matrix dominated process. Therefore no intraply damage or delaminations occur before the fracture load is reached. As such, no changes (damage) are recorded during loading by ultrasonic C-Scanning.

Based upon consistent analytical and experimental results it is evident that both the fracture loads and fracture modes are a function of angleply in the notched and unnotched tensile specimens tested during the course of this study. Figures 15, 16, and 17 show these results pictorially plotting in

respective order the fracture load and the mode of fracture as a function of ply orientations in solid, notched with a slit, and notched with a hole laminates.

Definite trends were established in terms of fracture load and type of fracture modes present in unidirectional and angleplied laminates. The fracture modes for the notch/slit and notch/hole laminates are the same except for the $[\pm 60]_s$ laminate where interply delamination near the hole-edge precedes specimen transverse fracture. The disparity between measured data and CODSTRAN predicted results is in part due to the excessive predicted stress concentration at the defect (slit/hole) edge. Though not completely determined at this time, it appears that this excessive stress concentration does not occur.

5.0 Conclusions

This study concentrated on fracture in graphite/epoxy unidirectional and angleplied composites subjected to a uniaxial applied stress. By assuming plane stress the analysis of the solid and notched laminates was reduced to a two dimensional problem. Given CODSTRAN results and correlation of these results with experimental data, the following conclusions concerning the fracture modes are made:

1. The Composite Durability Structural Analysis (CODSTRAN) computer code can accurately predict fracture modes of solid and notched composites on a ply by ply and interply delamination basis. In addition to identifying fracture modes CODSTRAN can be used to predict fracture patterns and extent and fracture loads.

2. The combined stress failure criteria used in CODSTRAN work well when coupled with a maximum stress/maximum strength proximity type algorithm for indicating fracture modes found in fiber composites.

3. The experimental techniques (ultrasonic C-Scanning (RUSCAN) and scanning electron microscopy (SEM)) used to verify CODSTRAN predicted results are excellent techniques for studying progressive fracture in composite materials.

4. In solid (unnotched) and notched (slit/hole) composite angleplied laminates the predominant fracture mode is a function of the ply orientation. The fracture modes due to a uniform stress field are: primarily longitudinal tension in solid laminates with ply orientations less than ±10°, longitudinal tension with intraply shearing at the notch tips in notched specimens with ply orientations less than ±10°, intraply shear in solid and notched specimens of orientations ±10° to ±45°, and transverse tension in solid and notched specimens with ply orientation greater than ±45°.

5. The adjacent ply relative rotation criterion accurately predicts in which angleplied laminates and at what loads interply delaminations, will occur at a notch tip. However, free edge delaminations are not predicted by CODSTRAN because the through-the-thickness free edge stresses are not calculated. The susceptibility of a laminate to delaminations is found to be a function of ply orientation with laminates in the ±30° to ±60° range most likely to delaminate.

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TABLE I. - FRACTURE MODES[a] OF $[\pm\theta]_s$ G/E LAMINATES
(PREDICTED BY CODSTRAN)

Notch type	Ply orientation; $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched -- solid	LT	LT S^3	LT S^3	LT S^3	I S	S	I S	TT	TT	TT
Notched -- thru slit	S^1 LT	S^1 LT	S^1 LT	S	S	I^4 S	I^4 S	I^4 TT S^2	TT	TT
Notched -- thru hole	S^1 LT	S^1 LT	S^1 LT	S	S LT	I^4 S	I^4 S TT	I^4 TT	TT	TT

[a]LT = Longitudinal tension.
TT = Transverse tension.
S = Intraply shear: (1) initial fracture due to intraply shear in the notch tip zone; (2) minimal intraply shearing during fracture; (3) some intraply shear occurring near constraints (grips); (4) delaminations occur in notch tip zone prior to any intraply damage.
I = Interply delamination.

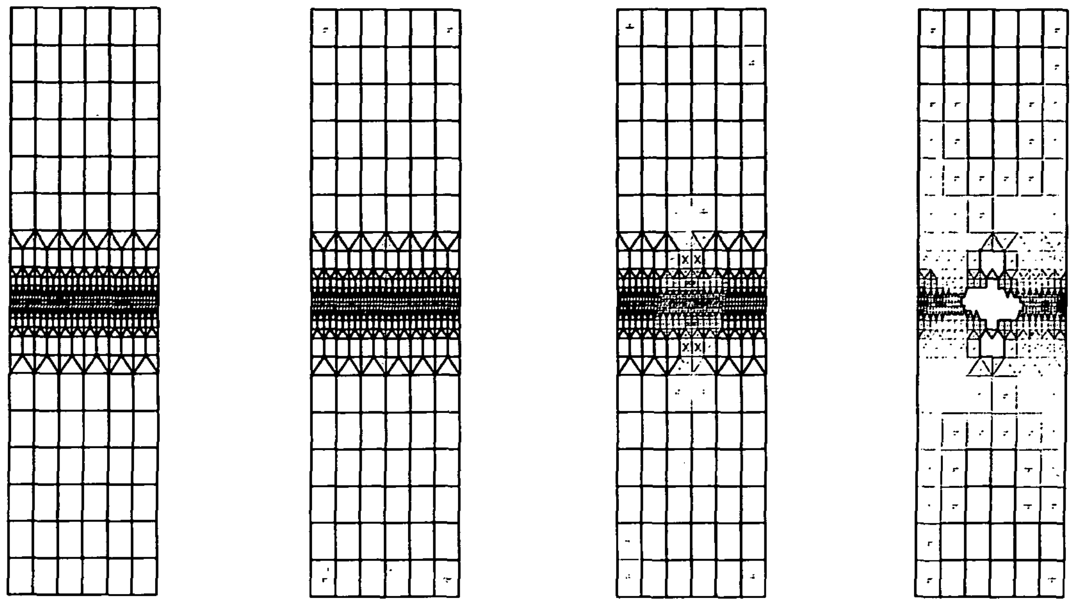
TABLE II. - FRACTURE MODES[a] OF $[\pm\theta]_s$ G/E LAMINATES
(DETERMINED BY SEM ANALYSIS)

Notch type	Ply configuration; $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched -- solid	LT	LT S	S LT	S LT	S LT	S LT	S LT	TT S	TT	TT
Notched -- thru slit	LT S	LT S	S LT	S LT	S LT	S LT	S LT	TT S	TT	TT
Notched -- thru hole	LT S	LT S	S LT	S LT	S LT	S LT	S LT	TT S	TT	TT

[a]LT = Longitudinal tension.
TT = Transverse tension.
S = Intraply shear.

TABLE III. - LAMINATE FRACTURE LOADS (P_f) AND PERCENT OF THE FRACTURE LOAD WHERE INTERNAL COMPOSITE DAMAGE WAS FIRST DETECTED (P_d) FOR FIBER COMPOSITE ANGLEPLIED LAMINATES WITH AND WITHOUT NOTCHES

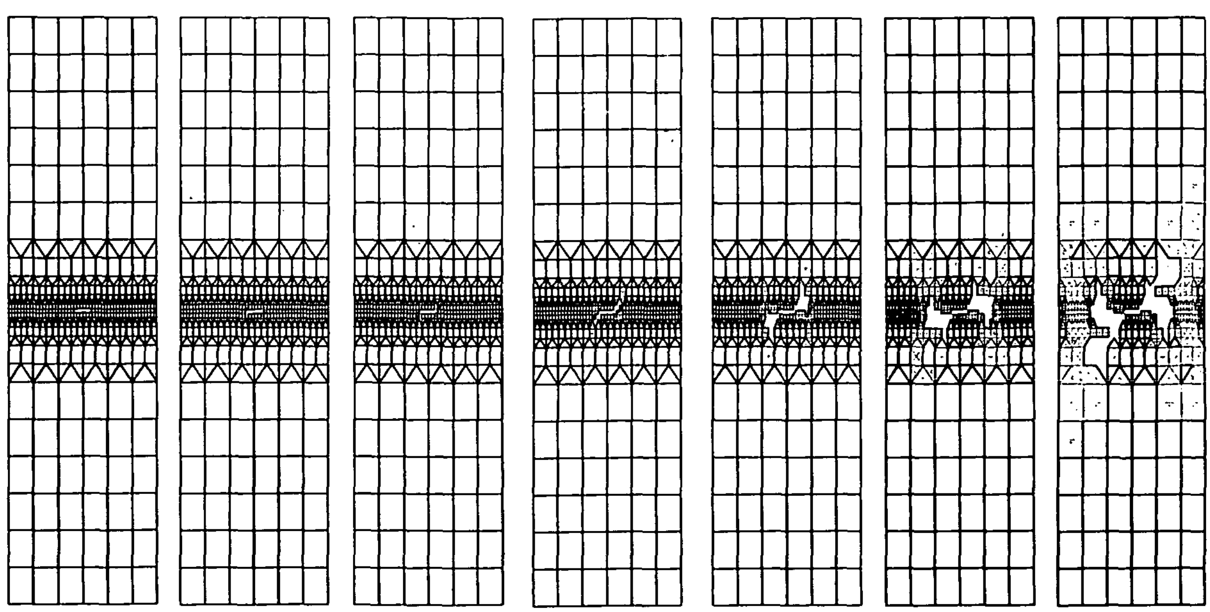
Ply orientation		$[0]_4$	$[\pm3]_s$	$[\pm5]_s$	$[\pm10]_s$	$[\pm15]_s$	$[\pm30]_s$	$[\pm45]_s$	$[\pm60]_s$	$[\pm75]_s$	$[90]_4$
RUSCAN results											
Solid specimen	P_f (lb)	8060	6500	5200	4500	3700	2620	900	420	220	260
	P_d (% of P_f)	100	100	100	100	95	100	100	100	100	100
With slit	P_f (lb)	7820	5500	4940	4160	2750	2150	880	320	180	180
	P_d (% of P_f)	100	100	56	87	100	100	66	100	100	100
With hole	P_f (lb)	6000	5720	4700	4240	3300	1750	950	360	220	120
	P_d (% of P_f)	100	79	69	77	92	100	100	100	100	100
CODSTRAN results											
Solid specimen	P_f (lb)	8300	7400	6950	5000	4400	2150	900	400	200	200
	P_d (% of P_f)	100	100	100	100	100	100	100	100	100	100
With slit	P_f (lb)	4500	3950	3600	2850	2250	1000	425	300	175	150
	P_d (% of P_f)	44	50	50	75	100	75	80	100	100	100
With hole	P_f (lb)	4700	3850	3500	2700	2150	1100	425	200	150	100
	P_d (% of P_f)	40	40	40	40	58	80	88	100	100	100



LOAD: 0 lb 5000 lb 5000 lb 5000 lb

ORIGINAL MESH: ELEMENTS 540
NODES 446
DEGREES OF FREEDOM 871

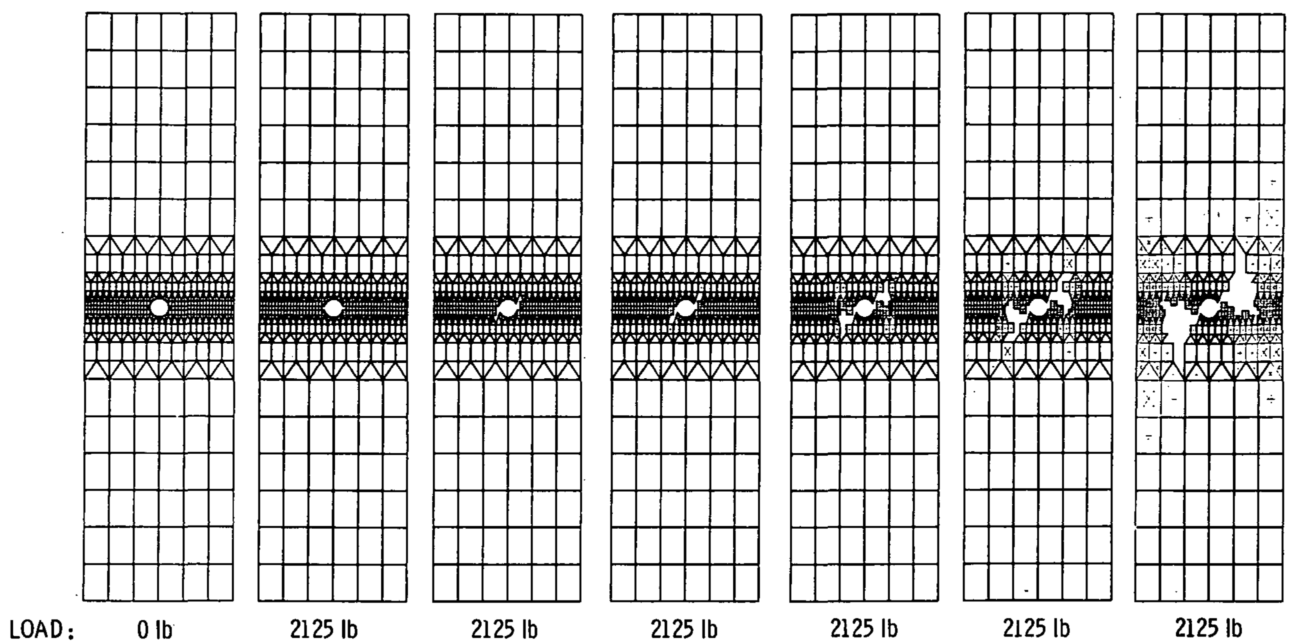
Figure 1. - CODSTRAN determined successive damage extent and defect growth as a result of progressive fracture in a $[\pm 15]_s$ graphite/epoxy solid laminate. Finite elements marked with a '+' denote damaged elements and those marked with an 'X' denote destroyed elements.



LOAD: 0 lb 2350 lb 2350 lb 2350 lb 2350 lb 2350 lb 2350 lb

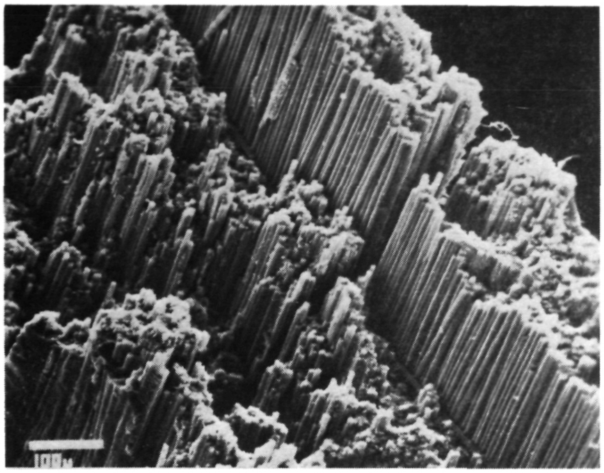
ORIGINAL MESH: ELEMENTS 534
NODES 446
DEGREES OF FREEDOM 871

Figure 2. - CODSTRAN determined successive damage extent and defect growth as a result of progressive fracture in a $[\pm 15]_s$ graphite/epoxy laminate with a 0.25 in. by 0.05 in. centered through-slit. Finite elements marked with a '+' denote damaged elements and those marked with an 'X' denote destroyed elements.

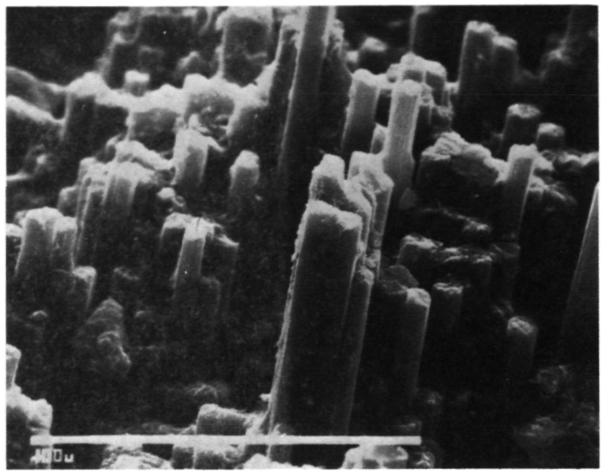


ORIGINAL MESH: ELEMENTS 534
NODES 442
DEGREES OF FREEDOM 863

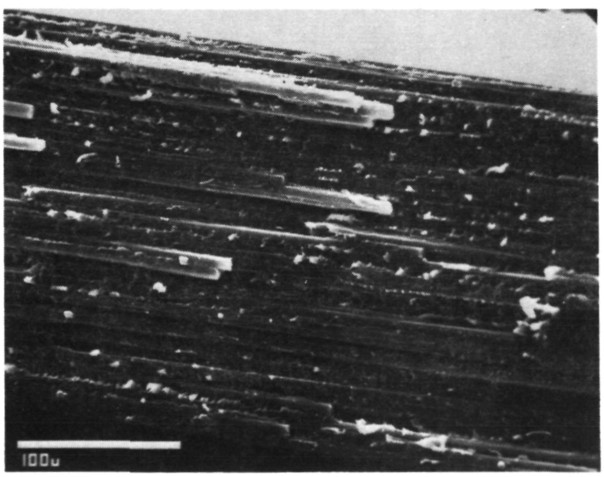
Figure 3. - CODSTRAN determined successive damage extent and defect growth as a result of progressive fracture in a $[\pm 15]_s$ graphite/epoxy laminate with a 0.25 in. diameter centered through-hole. Finite elements marked with a '+' denote damaged elements and those marked with an 'X' denote destroyed elements.



(a) Longitudinal tensile fracture characterized by a tiered surface caused by fiber fracture.

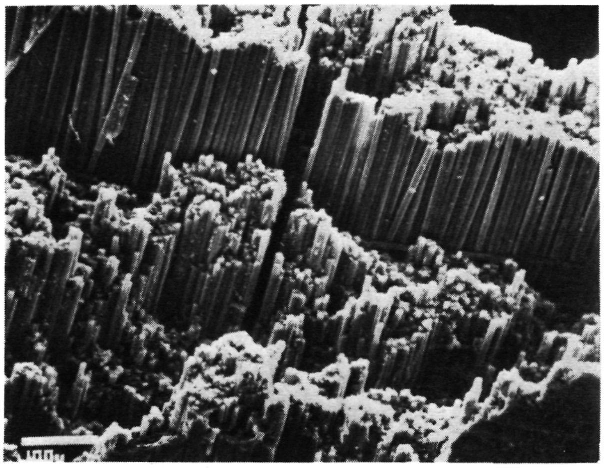


(b) Intralaminar shear fracture characterized by a surface with extensive matrix hackling.

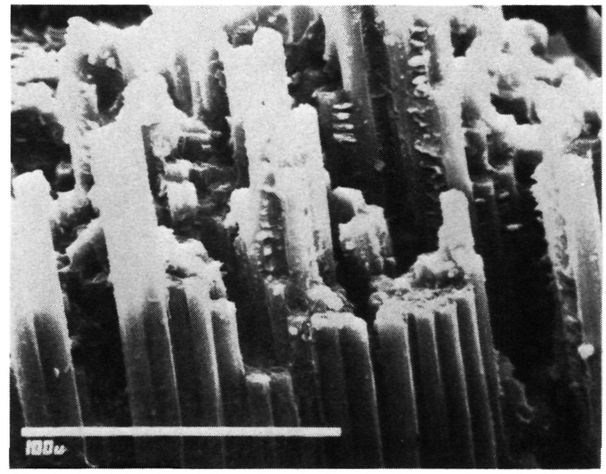


(c) Transverse tensile fracture characterized by smooth fiber surfaces with some apparent matrix cleavage.

Figure 4. - Typical fracture surfaces from unidirectional and angleplied graphite/epoxy composite laminates.



(a) Fiber fracture for the solid specimen.



(b) Notch/slit specimen (note the presence of matrix hackles).

Figure 5. - Photomicrographs of the fracture surface of the unidirectional laminate.

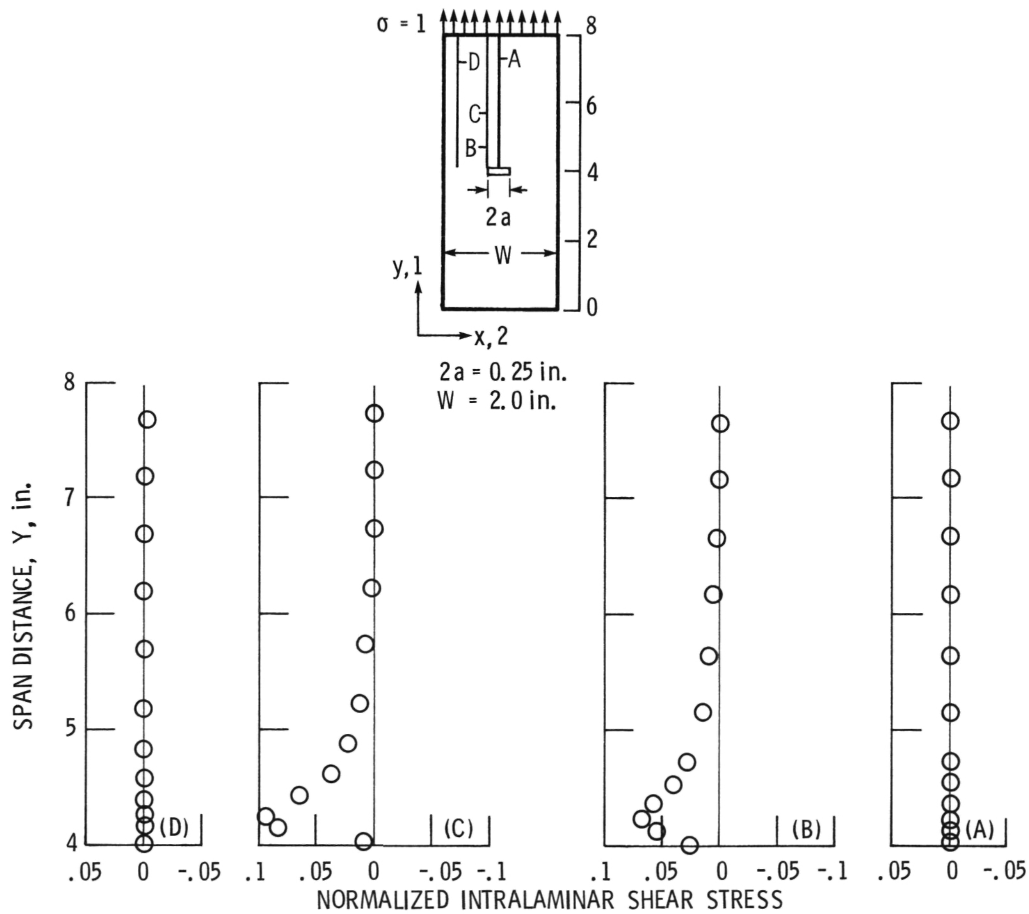
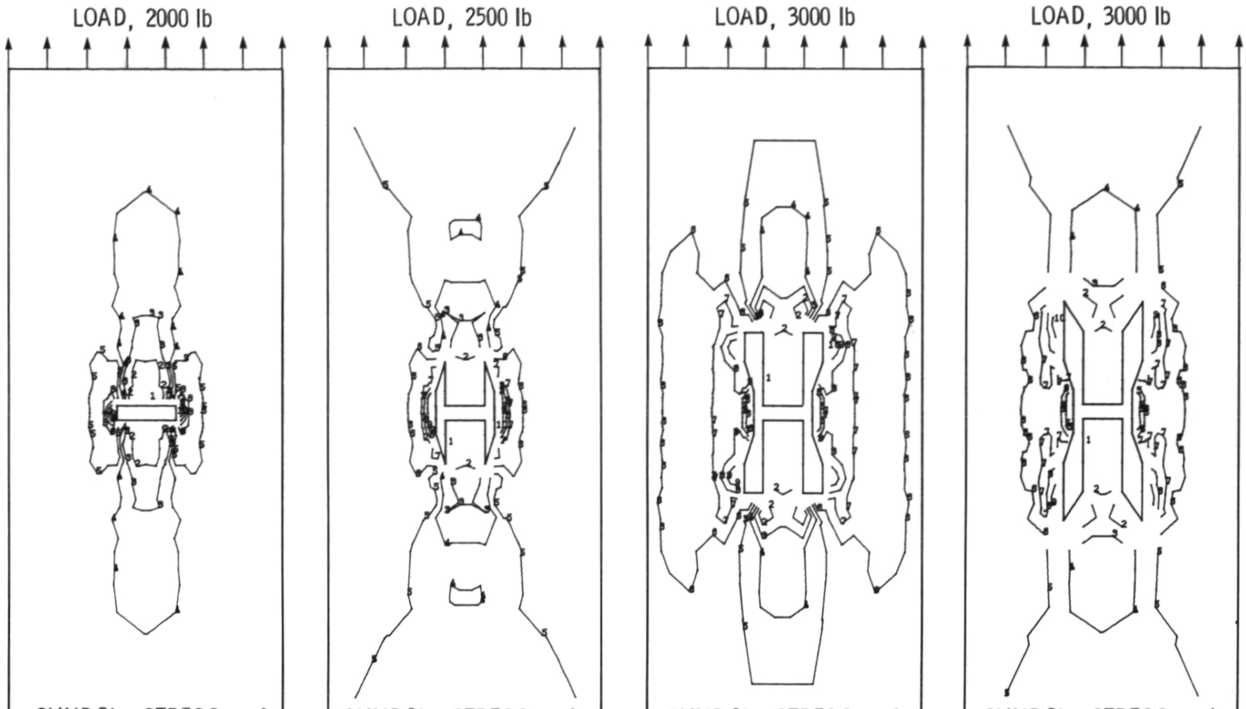


Figure 6. - Ply intralaminar shear stress (σ_{12}) magnitude profiles in the unidirectional graphite/epoxy (T300/934) composite with a centered through-slit.



SYMBOL	STRESS, psi	SYMBOL	STRESS, psi	SYMBOL	STRESS, psi	SYMBOL	STRESS, psi
1	1548	1	243	1	144	1	142
2	16337	2	16177	2	16950	2	19108
3	31126	3	32112	3	33756	3	38075
4	45915	4	48047	4	50562	4	57042
5	60704	5	63982	5	67368	5	76008
6	75493	6	79917	6	84175	6	94975
7	90282	7	95851	7	100981	7	113942
8	105071	8	111786	8	117787	8	132908
9	119860	9	127721	9	134593	9	151875
10	134649	10	143656	10	151399	10	170842

Figure 7. - Longitudinal stress contours in a notched, with a through-slit, unidirectional composite showing the effects of progressive fracture on stress concentrations. Predicted fracture load, 4500 lb.

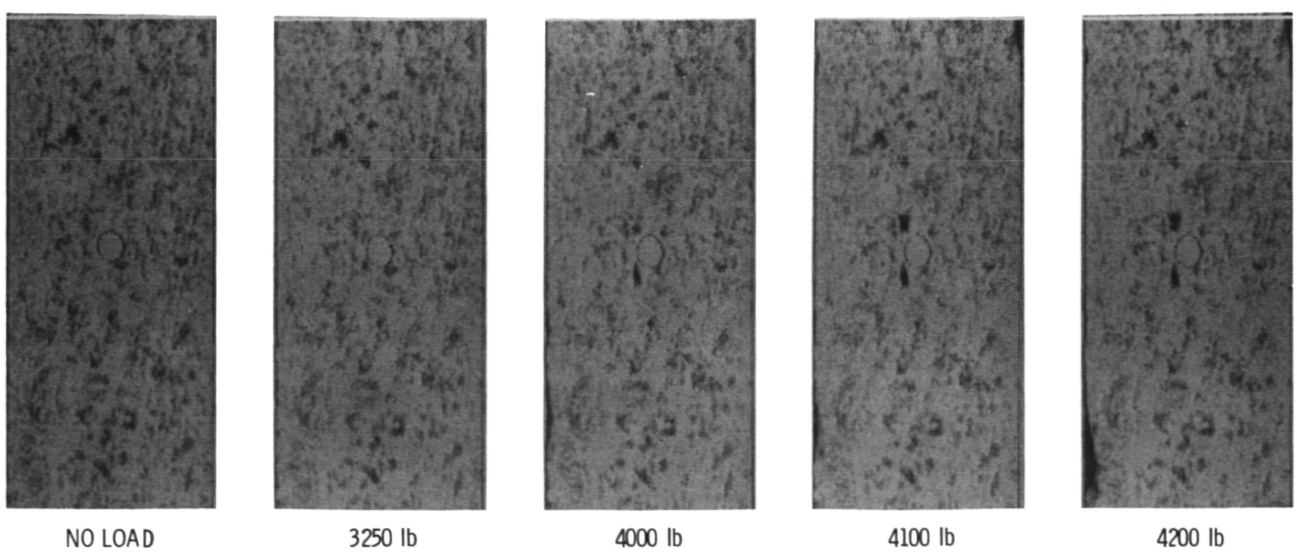
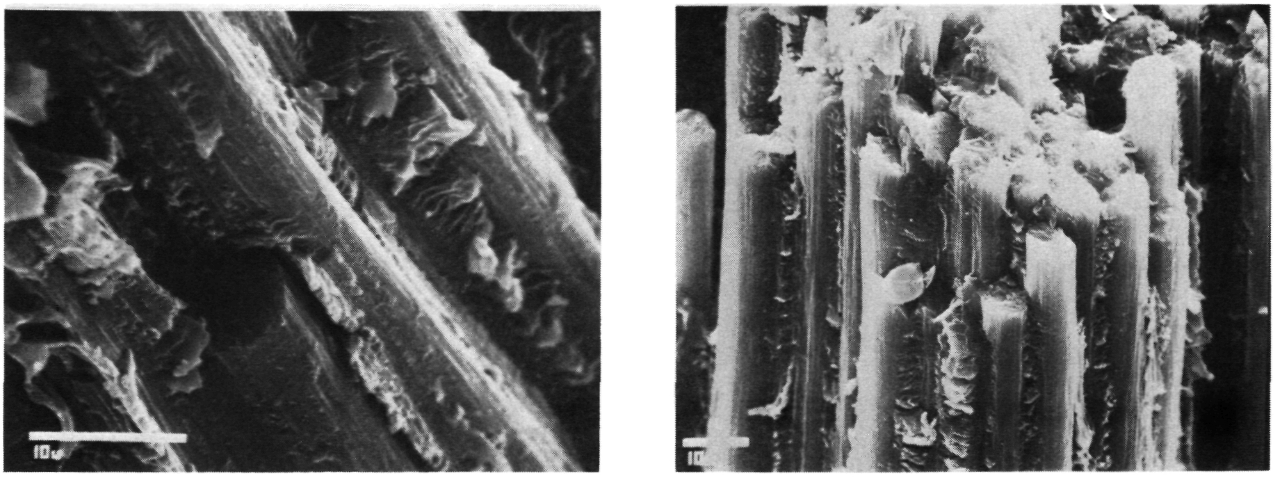
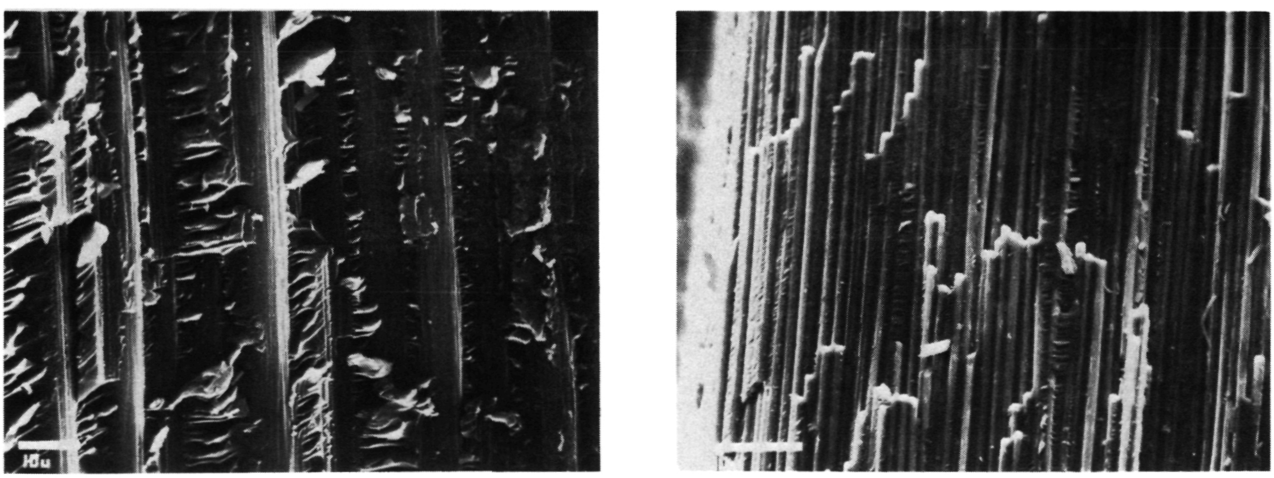


Figure 8. - C-Scan images of the $[\pm 10]_S$ laminate recorded at the indicated load increment depicting damage around the through-hole and edge delaminations prior to fracturing at 4240 lb.



(a) Notch/slit specimen. (b) Notch/hole specimen.

Figure 9. - Photomicrographs of the $[\pm 15]_S$ laminate show matrix hackles as the dominant microstructural characteristic indicative of an intraply shearing mode.



(a) Notch/slit specimen. (b) Notch/hole specimen.

Figure 10. - The dominant fracture surface characteristic for the $[\pm 45]_S$ laminate is matrix hackles.

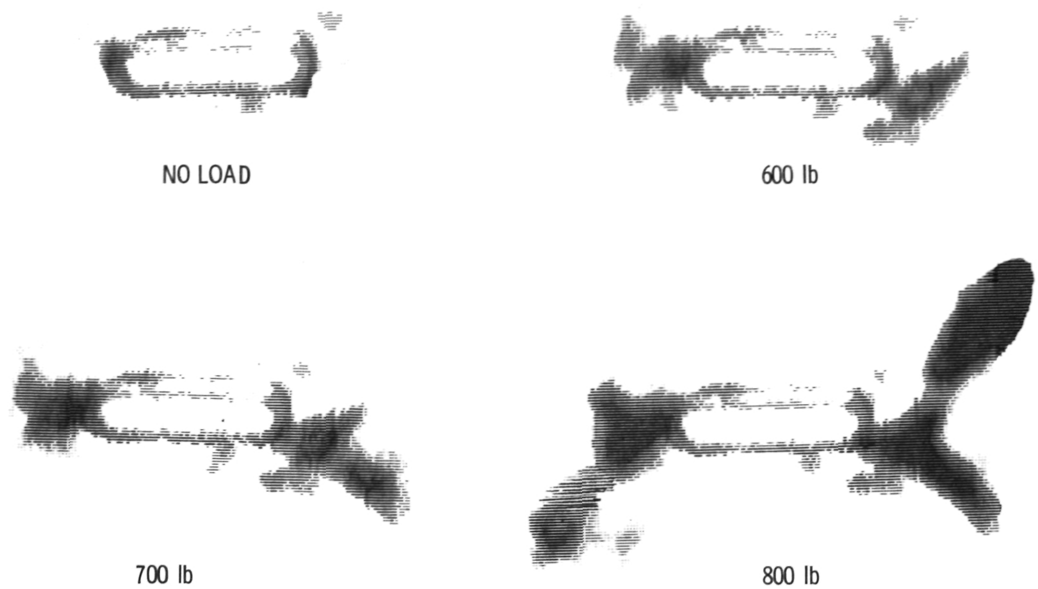


Figure 11. - C-Scan images of the $[\pm 45]_s$ laminate reveal an increase in delaminations at the tip of the notch/slit as the load increment increases until final fracture occurs at 880 lb.

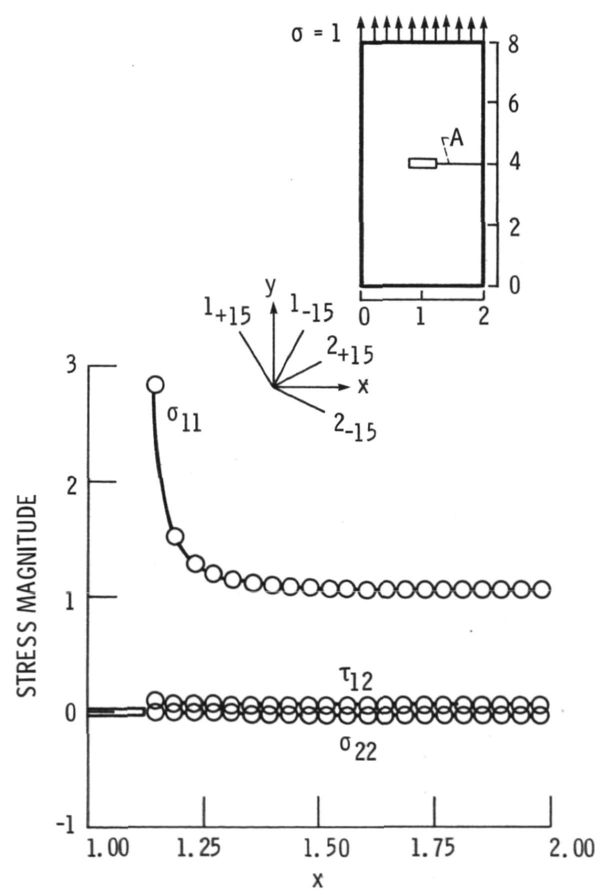


Figure 12. - Longitudinal (σ_{11}), transverse (σ_{22}), and shear (σ_{12}) stresses along line A in the -15° ply of a $[\pm 15]_s$ graphite/epoxy laminate with a centered through-slit subjected to a uniform stress state.

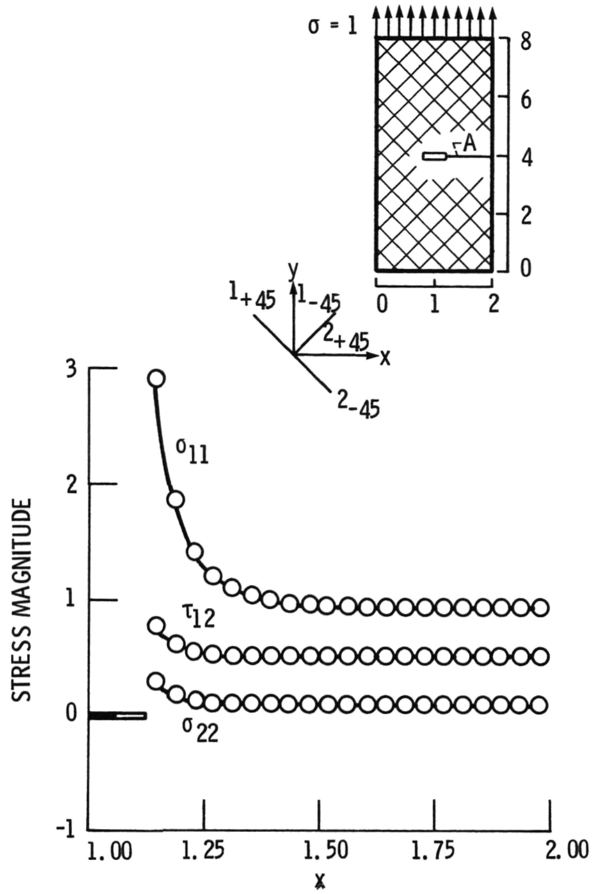
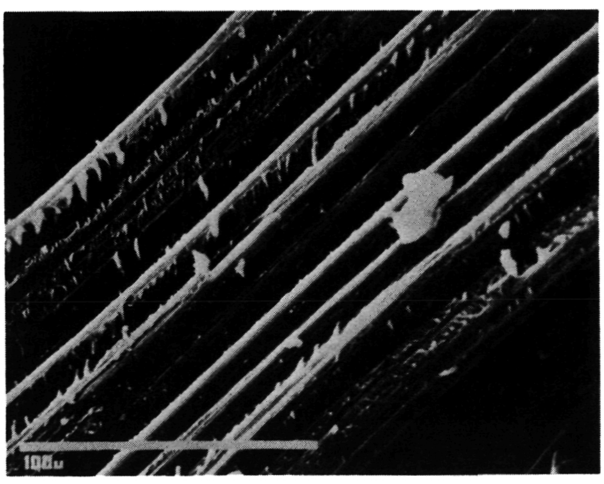
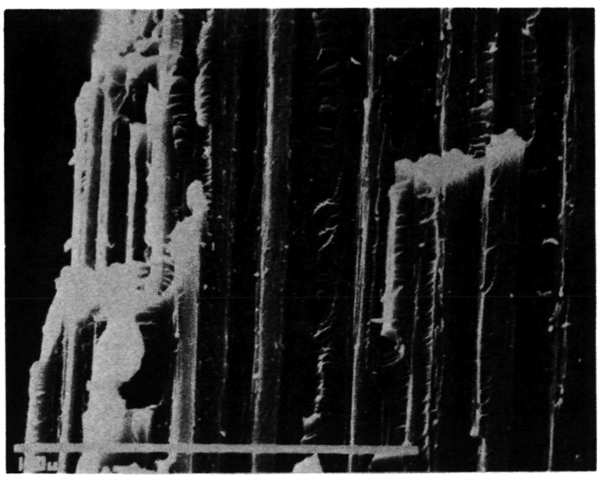


Figure 13. - Longitudinal (σ_{11}), transverse (σ_{22}), and shear (τ_{12}) stresses along line A in the -45° ply of a $[\pm 45]_s$ graphite/epoxy laminate with a centered through-slit subjected to a uniform stress state.



(a) $[\pm 60]_s$ solid specimen.



(b) $[\pm 75]_s$ notch/slit specimen consist of clean fiber surfaces and matrix cleavage associated with a transverse tensile mode of fracture.

Figure 14. - Fracture surface characteristics.

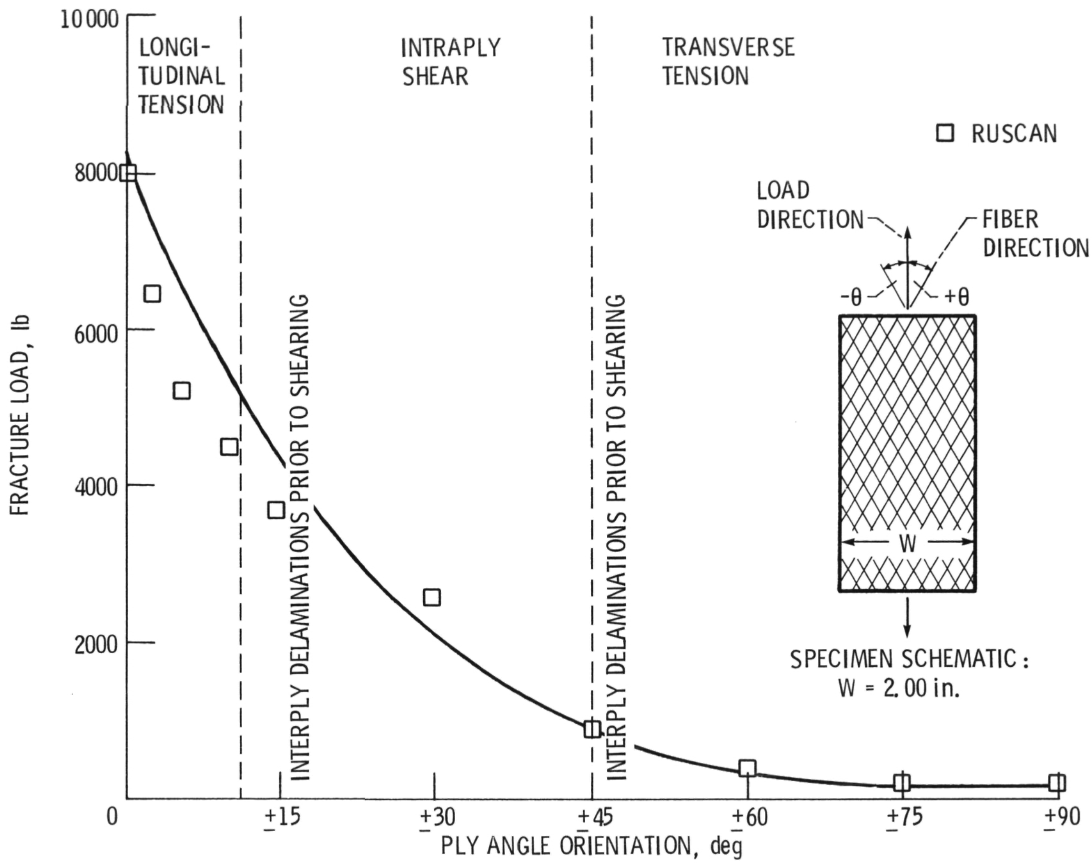


Figure 15. - Predominant fracture modes in the solid graphite/epoxy laminates. The presence of secondary modes are noted for individual angleplies.

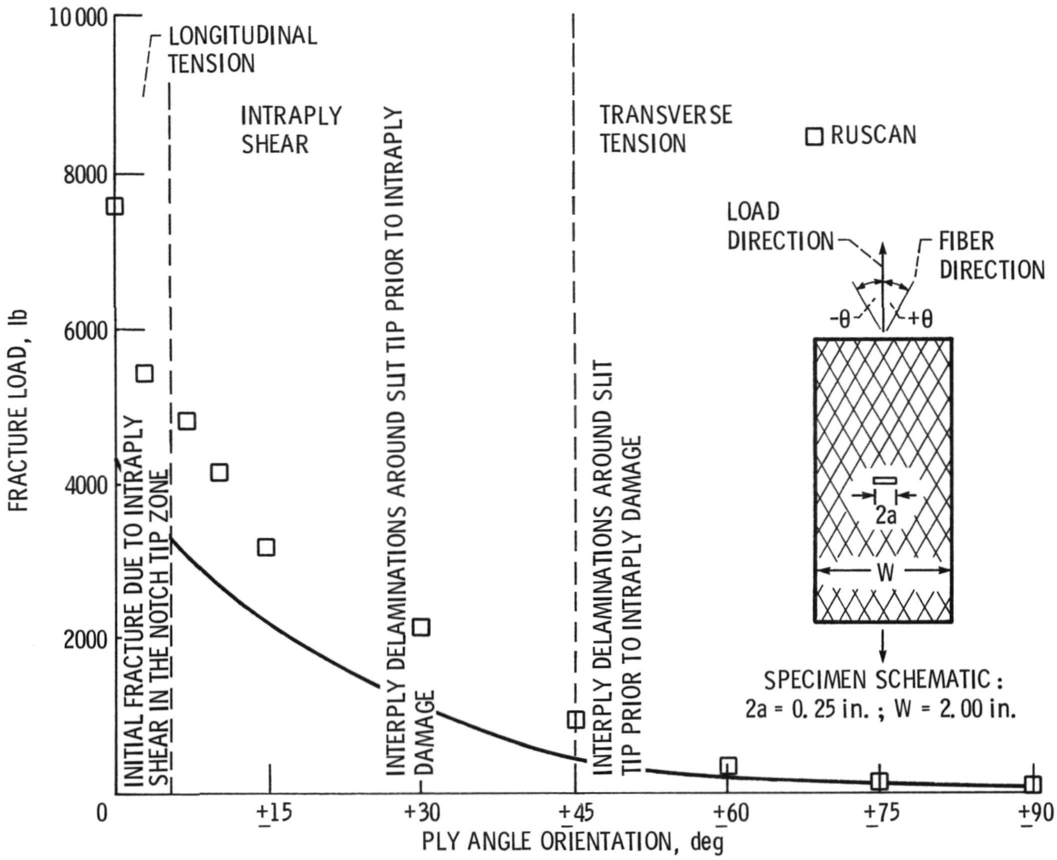


Figure 16. - Predominant fracture modes in the notched, with a through-slit, laminates. Presence of an initial or secondary mode is indicated for the individual angleply.

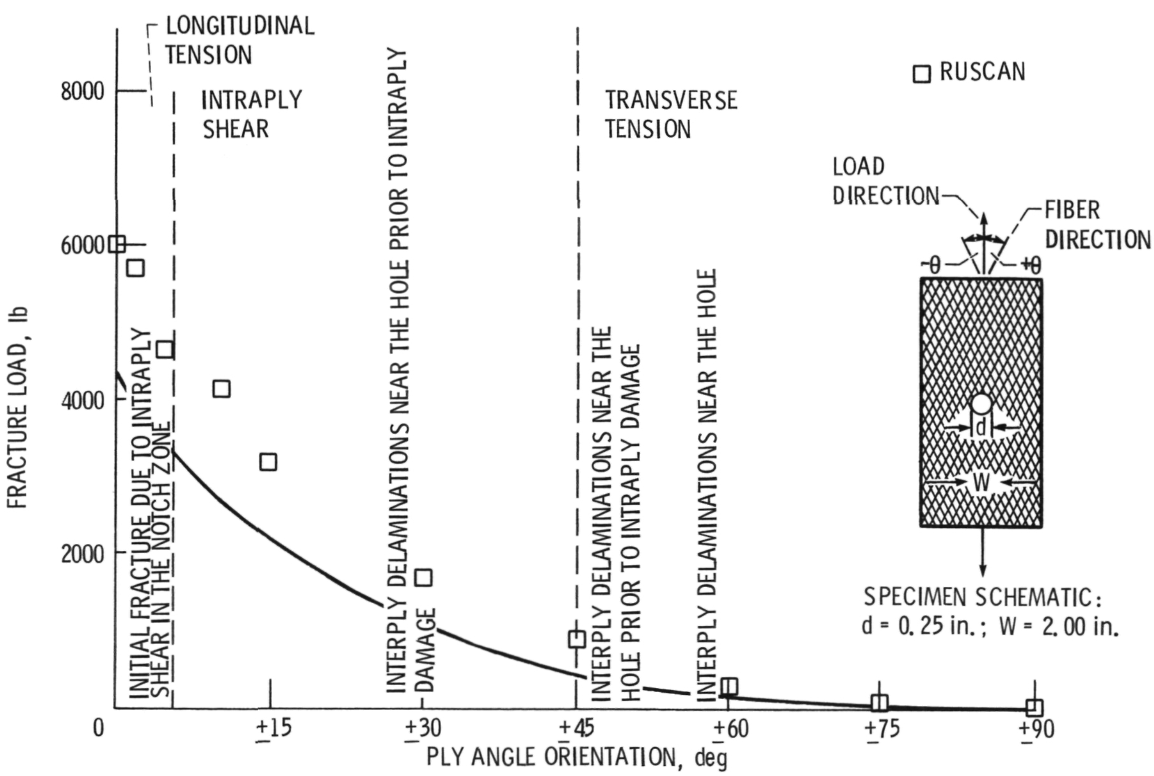


Figure 17. - Predominant fracture modes in the notched, with a through-hole, laminate. Presence of an initial or secondary mode is indicated for the individual angleply.

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15. Supplementary Notes

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16. Abstract

A unique Lewis Research Center analytical capability, the Composite Durability Structural Analysis (CODSTRAN) computer code is used to determine composite fracture. Fracture modes in solid and notched, unidirectional and angleplied graphite/epoxy composites were determined by using CODSTRAN. Experimental verification included both nondestructive (ultrasonic C-Scanning) and destructive (scanning electron microscopy) techniques. The fracture modes were found to be a function of ply orientations and whether the composite is notched or unnotched. Delaminations caused by stress concentrations around notch tips were also determined. Results indicate that the composite mechanics, structural analysis, laminate analysis, and fracture criteria modules embedded in CODSTRAN are valid for determining composite fracture modes.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Composites; Graphite/epoxy; Fracture; Fracture modes; Stress concentrations; Finite element analysis; Fractography	Unclassified - unlimited STAR Category 24

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